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Determination of Model Parameters of PV Modules Using a Low Cost I-V Tracer

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Abstract—**Tracing current-voltage characteristics of photovoltaic modules in open field conditions is a very important task in degradation and fault diagnosis. Usually this is done by using expensive DC electronic loads, many times not suitable for outdoor tests. The health state of photovoltaic modules can be evaluated by monitoring the parameters of its exponential model, mainly the series resistance. This can be done by tracing the current-voltage characteristics in field conditions from which those model parameters can be extracted. This paper presents the determination of the parameters of the exponential model of photovoltaic modules from experimental current-voltage curves using a low cost I-V tracer developed in previous works.**

Keywords – Photovoltaic Modules; Determidation of Model Paramters, I-V Tracer; Degradation Diagnosis of PV Modules.

I. INTRODUCTION

All over the world, a widespread use of photovoltaic (PV) energy as a renewable source, either in centralized or distributed systems, is now a reality [1] because of increased interest in environmental issues, absence of fuel cost, little maintenance, and no noise and wear due to the absence of moving parts [2]. On the other hand, natural resources of fossil and nuclear fuels are estimated to decrease drastically in this century and solar energy is practically an endless source [3]. The growth of the installed PV systems has experienced an exponential increase in many countries in last decade and this trend is expected to continue and even to accelerate over the coming decades [4]-[6].

PV modules are usually guaranteed for more than 25 years by manufacturers which estimate this period through accelerated indoor life-cycle tests during their design procedure [7]. In spite of this extended guarantee, their performance decreases over the time and fault conditions have been reported [6], [7]. Some PV modules degrade or even fail when operating outdoors for extended periods, and that can occur in a number of ways [8]. Degradation is the main reason for module loss of performance and as field experience has indicated, losses have been associated with mechanisms external to the cells such as solder bonds, encapsulate browning, delamination and interconnect issues [7]. In the degradation diagnosis in PV modules, the Current-Voltage (I-V) characteristics are usually used, as well as parameters obtained from them, like short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), voltage and current at the Maximum Power Point (MPP), respectively V_{mpp} and I_{mpp} [1], and other parameters like the series resistance [9]-[12]. I-V characteristics can be monitored and the results used to investigate and compare the actual power produced by modules under realistic operating conditions with the expected yield to make these systems more cost effective [1], [13]. They can also be used by designers in power converter systems.

Photovoltaic modules are usually tested using expensive electronic DC loads, which can vary the load resistance over the entire range in a very short time. Anyway, by using quite simple and much cheaper circuits, it is also possible to build an electronic DC load taking advantage of a suitable operation of a power MOSFET, as described in [1], [14]. In fact, a power MOSFET operating in the active region can be used as an electronic load to test PV modules [13]-[16]. Such simple and/or low cost electronic circuits have been developed in recent years to trace the I-V characteristics of PV cells [17] or modules [13], [18]. In [14] an electronic circuit was presented to test PV modules by tracing their I-V and P-V characteristics. It was based on a power MOSFET with an improved gate-source voltage (V_{GS}) generation strategy in order to improve the I-V tracing on an oscilloscope. This low cost I-V tracer was improved in [1] and a LabVIEW interface was developed for data acquisition and analysis. In this paper, it is used for determination of the exponential model parameters of PV modules. This is very important for degradation diagnosis, design of the MPP tracking and control strategies, as well as evaluation of photovoltaic plants behavior in various irradiance, temperature and load conditions.

II. Determination of Model Parameters From Experimental I-V Curves

A. The Model of PV Modules

The equivalent circuit of the single-diode model for PV modules is shown in Fig. 1(a) and the corresponding I-V characteristic based on the single exponential model [19] is given by:

$$I_{pv} = I_{ph} - I_0\left(\exp\left(\frac{V_{pv} + R_s I_{pv}}{V_t}\right) - 1\right) - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \qquad (1)$$

In the above equation, the thermal voltage, V_t, of the array with N_s cells connected in series is:

$$V_t = \frac{N_s AkT}{q} \qquad (2)$$

Where:

I_{ph} is the module photocurrent;

I_0 is the inverse saturation current of the diode;

R_s is the module series resistance;

R_{sh} is the module parallel resistance;

A is the ideality factor of the diode;

k=1.38×10^{-23}J/ºK is the Boltzmann constant;

q=1.602×10^{-19} C is the charge of the electron;

T is the working temperature of the PV module, in Kelvin.

It is very common to consider the module parallel resistance R_{sh} high enough to be neglected [9], [10] and [12]. The simplified equivalent circuit is shown in Fig. 1(b) and the last term of the single exponential model (1) disappears:

$$I_{pv} = I_{ph} - I_0\left(\exp\left(\frac{V_{pv} + R_s I_{pv}}{V_t}\right) - 1\right) \qquad (3)$$

Sometimes the term “-1” in (3) is also neglected since in silicon devices, the inverse saturation current is very small compared to the exponential term [19]. The result is the well-known four parameters model [9]-[11] and [20]. In this model, the four parameters to be determined are I_{ph}, I_0, V_t and R_s. It is important to notice that the series resistance is one of the most important parameters, which characterizes the photovoltaic module health state [20].

B. The Model Parameters Extraction

In recent years several methods have been presented in the literature, for extracting the PV module parameters. Some of them from datasheet values [19], but the majority is based on measurements of the I-V characteristics [9]-[11], [20].

The simplified I-V characteristic (3) contains three remarkable couples of points, (0, I_{sc}), (V_{oc}, 0) and (V_{mpp}, I_{mpp}), which can be used to determine the unknown parameters as follows:

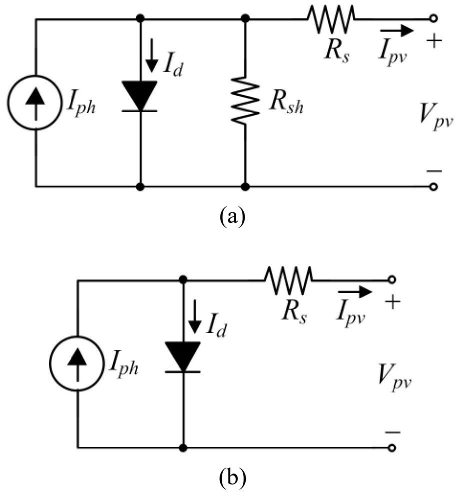

Figure 1. Equivalent circuit of a PV module: (a) Full single exponential model; (b) Simplified model.

$$I_{sc} = I_{ph} - I_0\left(\exp\left(\frac{R_s I_{sc}}{V_t}\right) - 1\right) \qquad (4a)$$

$$0 = I_{ph} - I_0\left(\exp\left(\frac{V_{oc}}{V_t}\right) - 1\right) \qquad (4b)$$

$$I_{MPP} = I_{ph} - I_0\left(\exp\left(\frac{V_{mpp} + R_s I_{mpp}}{V_t}\right) - 1\right) \qquad (4c)$$

The above system of three equations has four unknown parameters. To solve this problem, without using numerical methods or other advanced techniques, it is a common practice to consider that the module photocurrent is approximately equal to the short-circuit current ($I_{ph} \approx I_{sc}$), [9], [10] and [20]. Considering this simplification, several approaches have been used to find the solution of (4) in view of determination of the unknown parameters I_0, V_t and R_s. In this work three solutions are used and compared. The first is nominated method 1 and is as follows [10]:

$$V_t = \frac{(2V_{mpp} - V_{oc})(I_{sc} - I_{mpp})}{I_{sc} + (I_{sc} - I_{mpp})\ln\left(1 - \frac{I_{mpp}}{I_{sc}}\right)} \qquad (5a)$$

$$I_0 = I_{sc}\exp\left(-\frac{V_{oc}}{V_t}\right) \qquad (5b)$$

$$R_s = \frac{V_t \ln\left(1 - \frac{I_{mpp}}{I_{sc}}\right) + V_{oc} - V_{mpp}}{I_{mpp}} \qquad (5c)$$

The second method is a slightly different solution presented in [20] that neglects the term “-1” in (3), and will be nominated by method 2. The third solution, nominated method 3, was used in [9] and is given by:

$$R_s = -M\frac{I_{sc}}{I_{mpp}} + \frac{V_{mpp}}{I_{mpp}}\left(1 - \frac{I_{sc}}{I_{mpp}}\right) \tag{6a}$$

$$V_t = -(M + R_s)I_{sc} \tag{6b}$$

$$I_0 = I_{sc}\exp\left(-\frac{V_{oc}}{V_t}\right) \tag{6c}$$

Where:

$$M = \left.\frac{dV}{dI}\right|_{oc} = \frac{V_{oc}}{I_{sc}}\left(-5.411\frac{I_{mpp}V_{mpp}}{I_{sc}V_{oc}} + \right. \\ \left. + 6.45\frac{V_{mpp}}{V_{oc}} + 3.417\frac{I_{mpp}}{I_{sc}} - 4.422\right) \tag{7}$$

The determination of these model parameters using the above three methods is presented in section IV by using the I-V tracer [1], which is shortly described in the next section.

III. The Low Cost I-V Tracer

The basic circuit of the I-V tracer with measurement resistances is shown in Fig. 2. A general diagram is presented in Fig. 3 and all electronic circuits are presented in detail in [1]. The tracing of the I-V and P-V characteristics is achieved by using the power MOSFET as an electronic fast continuous varying load, which principle of operation has been described in [14]. A suitable gate-source voltage (V_{GS}) is generated in

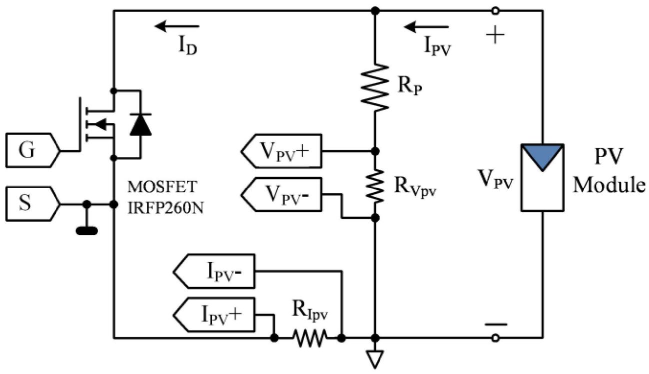

Figure 2. Basic circuit of the I-V tracer with measurement resistances.

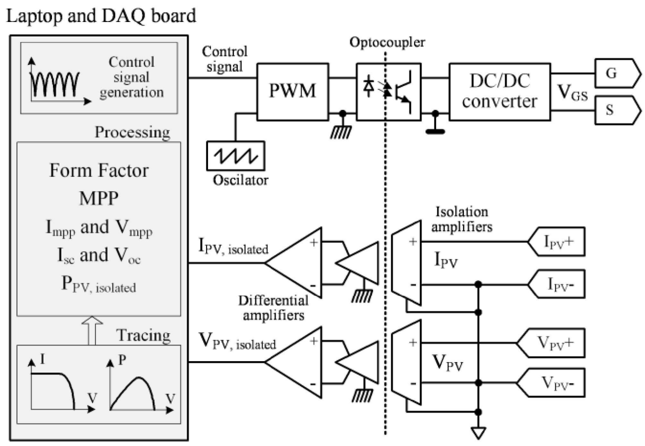

Figure 3. General diagram of the I-V tracer.

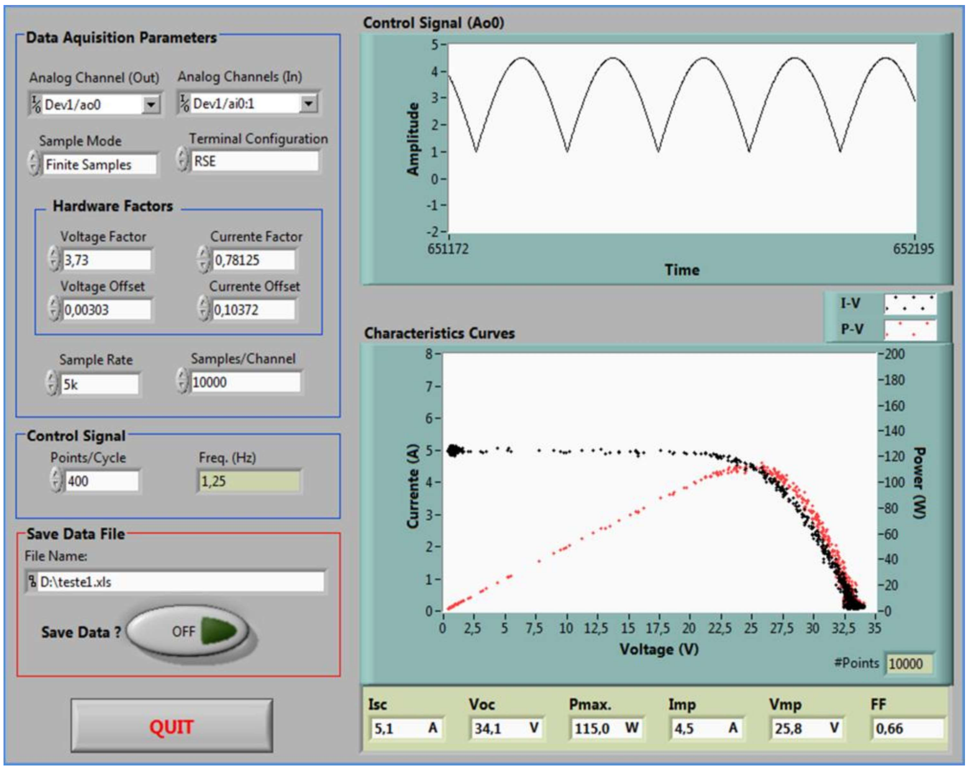

Figure 4. User interface of the developed I-V tracer.

order to drive the MOSFET across the active region where the drain current follows V_{GS} linearly. Galvanic isolation is provided and the output voltage and current signals are sampled by a DAQ board to trace the I-V and P-V characteristics using a laptop and virtual instruments developed in a *LabVIEW* application [1]. Besides the functionality of continuous tracing of I-V characteristics, this application provides very important parameters such as V_{oc}, I_{sc}, V_{mpp}, I_{mpp} and form factor. Furthermore, all the acquired data can be filtered and saved for digital processing and analysis.

In this work the extracted parameters from the measured I-V characteristic are used for determination of the model parameters of PV modules. Fig. 4 shows the user interface of the I-V tracer where the control signal that generates V_{GS} for the power MOSFET and the I-V and P-V characteristics can be seen on the right side.

In spite of the improved characteristics described in [1] and [14], the developed electronic circuits keep a quite simple design and of low cost. Table I shows the estimated cost of the different parts of the equipment. The development cost of the LabVIEW application is not included since it is carried out once and its weight would be as much lower the greater the number of units produced. Some pictures of the prototype is shown in Fig. 5.

Recent developments of [1] have introduced new modules for PV arrays up to 15 A, 1000 V. These developments include two IGBTs and their driver circuits to charge and discharge two series connected capacitors used as load.

A simplified comparison, regarding the main characteristics, of the developed I-V tracer with similar commercial equipment is shown in Table II. Of course, the comparison is not complete and, apart from the electronic circuits, the developed instrument is an open platform and the comparison is not easy and a careful analysis should be done.

IV. Experimental Determination of Model Parameters Using The I-V Tracer

As described in section II, the model parameters of the exponential model (3) of PV modules can be extracted from the experimental I-V curves. To demonstrate this application with the I-V tracer, and using the three approaches described in section II, the PV module FTS-220P was used which has 60 cells in series, and the following parameters at Standard Test Conditions (STC: cell temperature of 25°C and irradiance of 1000 W/m^2 with air mass of 1.5): 220 W, V_{oc}=36.76 V, I_{sc}=8.30 A, V_{mpp}=29.38 V, I_{mpp}=7.51 A.

Using the measured values at three important points, short

TABLE I. Estimated Cost of the Different Parts of the equipment

Components of the equipment	Cost	%
Measurement board	66 €	13%
Power board	36 €	7%
Battery and power supply board	73 €	14%
Controller board	42 €	8%
PCBs manufacturing	60 €	12%
Box and other accessories	60 €	12%
DAQ board	170 €	34%
Total	506 €	100%

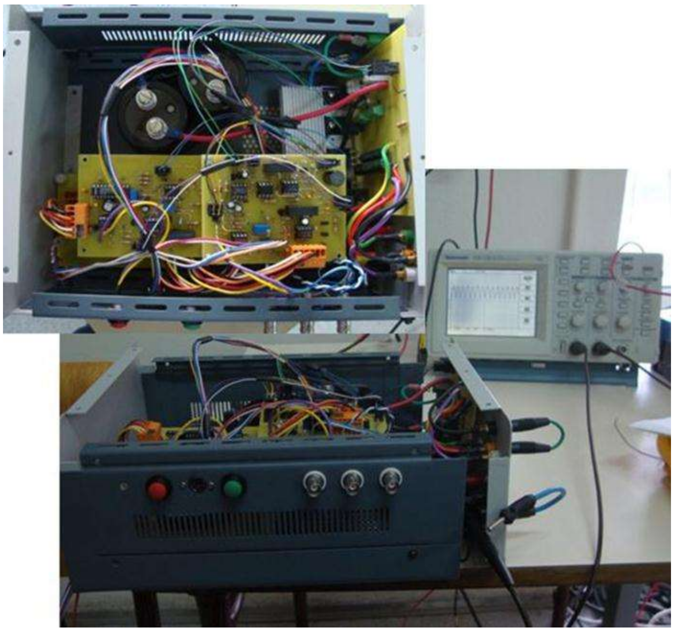

Figure 5. Pictures of the developed equipment.

TABLE II. Comparion of the Develoed I-V Tracer witj Comercial Equipment

	Developed I-V tracer	Vision Tec-VS6810	SUPSI-MPPT3	Amprobe Solar 600	Daystar DS-100C	EKO MP-170	HT I-V 400	Solmetric PVA 600	PVE PVPM6020
PV Modules	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PV arrays	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
Voltage range (V)	60(*)/1000(**)	2/20/200	200/100/50/20	60/10	600/60/6	1000-10	1000-5	600-20	600/300/100/25
Current range (A)	6(*)/15(**)	10/1/0.1	10/20/5	12/10	100/10	20-1	10-0.1	20-1	20/10/5/2
Isolation	Yes	n/a	Yes	Yes	n/a	n/a	Yes	Yes	n/a
Price (€)	<600(***)	n/a	n/a	1295	17705	4900	3514	2280	>7800
V_{oc}, I_{sc}, V_{MPP}, I_{MPP}, FF	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R_s/R_p	Yes/No	Yes/No	No/No	No/No	No/No	No/No	Yes/No	Yes/No	Yes/Yes
Max. I-V sweep time (s)	Configurable	7-0.1	3-1	9.99	5	n/a	n/a	0.24-0.08	2

(*) For PV modules and continuous tracing (can be improved with higher voltage MOSFETs in parallel).
(**) For PV strings, single trace.
(***) Does not include the LabVIEW application and requires an oscilloscope or a laptop.

circuit, open circuit and maximum power point, respectively, (0,6.2), (34,0) and (25,5.45), and the three methods referred in section II it is now possible to calculate the model parameters I_0, V_t and R_s. The experimental curve obtained using the I-V tracer is shown in Fig. 6. The extracted parameters are shown in Table III. The values of R_s include the resistance of the cables from the roof to the laboratory.

The different extracted values obtained using the three methods have effect on the shape of the simulated I-V and P-V curves using the calculated parameters and model (3), as shown in Fig. 7 and Fig. 8. Each one of the methods has its own performance. Method 2 [20] has a very good approximation between the MPP and open circuit point, but has the biggest overestimation for voltages lower than V_{mpp}. Method 3 [9], gives better approximation between short circuit point and MPP of the curve, but for voltages higher than V_{mpp} the overestimation is the highest of all methods. Method 1 [10] extracts the parameters that produce the better overall approximation along the I-V characteristic.

The experimental and simulated P-V curves, using extracted parameters by different methods, are shown in Fig. 8. By comparing the simulated curves with the experimental one, it can be seen that the P-V characteristic of method 2 [20] gives the worst estimation of the MPP but the best approximation above V_{mpp}. Method 3 [9] has a very good approximation for voltage lower than V_{mpp} but the worst approximation above this point. Method 1 [10] has a better overall approximation to the experimental curve.

The P-V curve is very important since it can be used for MPP tracking [21] and the degradation diagnosis of PV modules because of the decrease of the maximum power available at STC. This can be detected by monitoring R_s over time and, therefore, the monitoring of this parameter can give important information about the health condition of the PV module.

V CONCLUSIONS

Tracing I-V characteristics and monitoring the model parameters is very important for fault and degradation diagnosis of photovoltaic modules, for the design of maximum power point tracking and control strategies, as well as for the evaluation of photovoltaic plants behavior in various irradiance, temperature and load conditions. This paper is a contribution for this purpose and presents the determination of the parameters I_0, V_t and R_s of the exponential model of photovoltaic modules obtained from experimental I-V curves in field operating conditions. This was done using a low cost I-V tracer with a LabVIEW application which was previously

TABLE III. EXTRACTED PARAMETERS USING MEASUREED VALUES.

Method	R_s (Ω)	I_0 (A)	V_t (V)
Method 1 [10]	0.599	3.29E-5	2.797
Method 2 [20]	0.969	4.53E-8	1.814
Method 3 [9]	0.375	2.76E-6	3.391

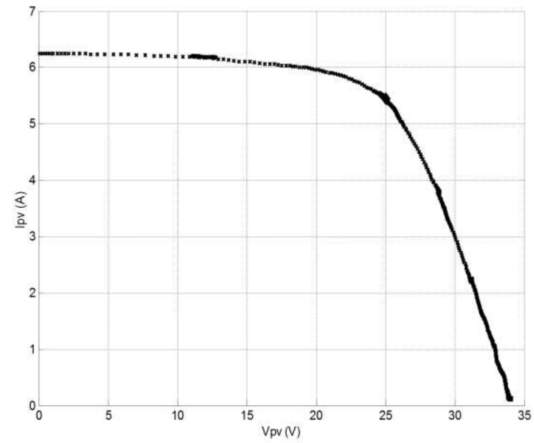

Figure 6. Experimental curve of the PV module FTS-220P obtained using the I-V tracer.

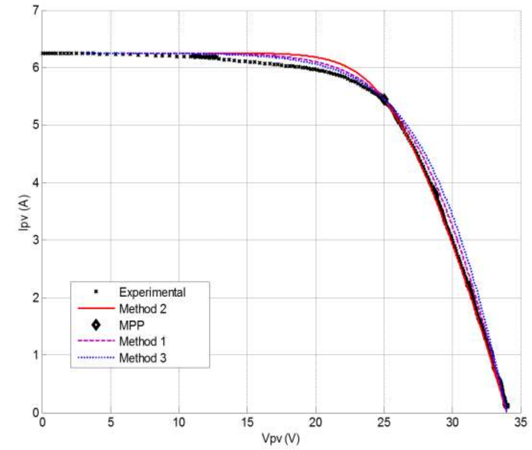

Figure 7. Experimental and simulated I-V curves using extracted parameters by different methods.

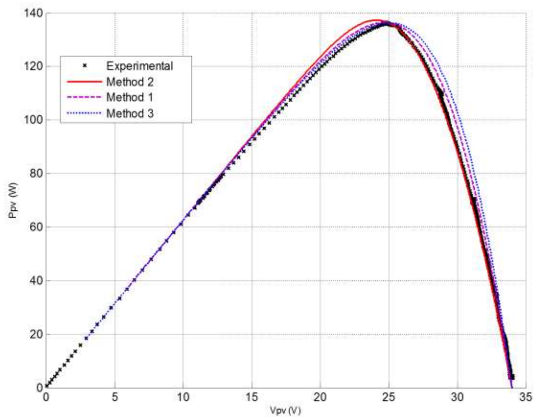

Figure 8. Experimental and simulated P-V curves using extracted parameters by different methods.

developed. The parameters are extracted from three points of measured I-V characteristics: short circuit, open circuit and maximum power point operation. This was done using three different approaches [9], [10] and [10], and the results have been compared in section IV.

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